

Multiple scattering in observations of the GPM dual-frequency precipitation radar: where we are, where to go

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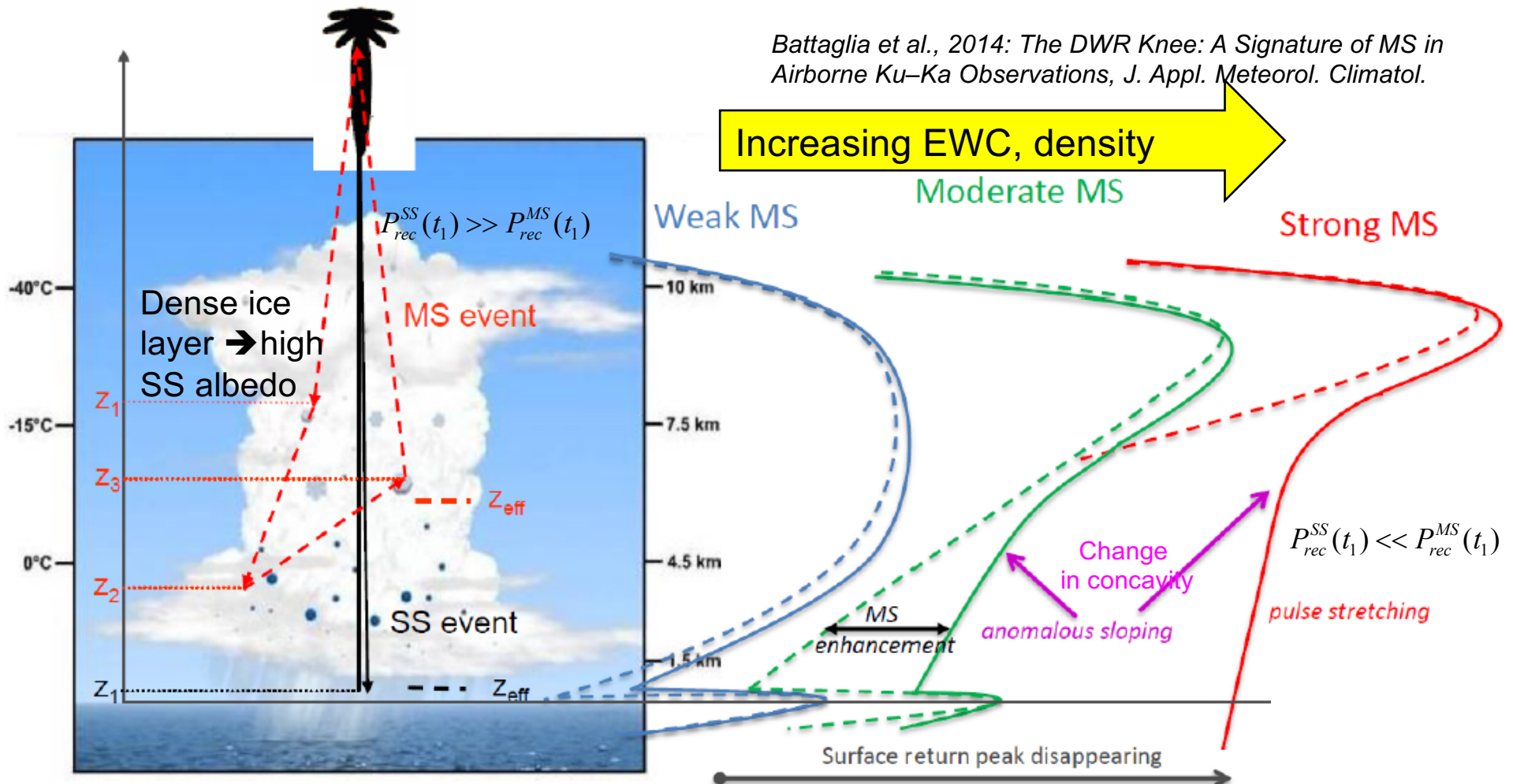
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Advanced Radar Research Center. National Weather Center. Norman. Oklahoma

Signatures of multiple scattering (MS)



MS enhancement, anomalous sloping, pulse stretching (ghost echoes)

disappearance of surface peak. All difficult to identify if only one frequency available \rightarrow MS is obvious only when overwhelming single scattering

With GPM we have also a detectability issue (we may lose the MS tail before reaching the surface)

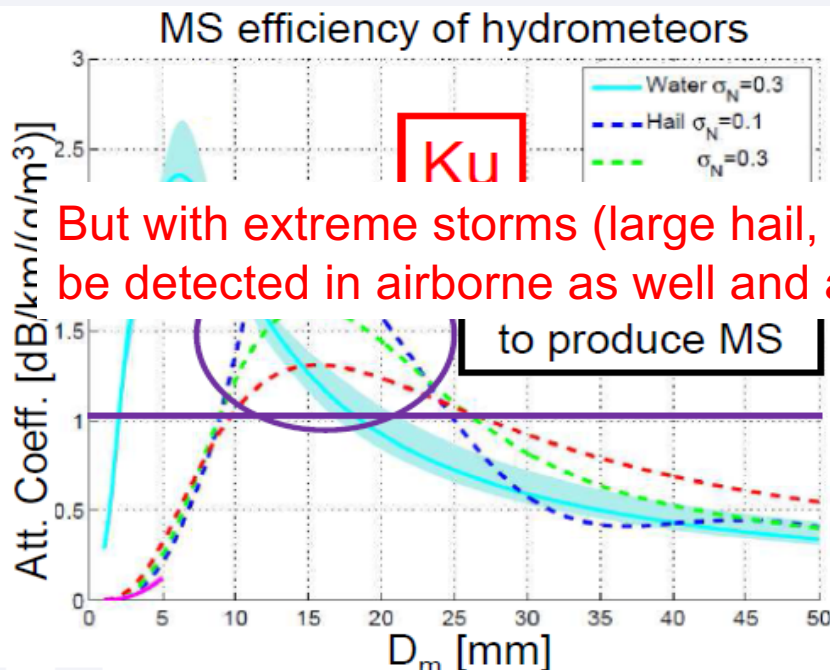
Key ingredients for MS

High extinction (attenuation) $k_{att} \rightarrow$ more MS at higher frequencies ($k_{att,Ku} \approx 2 * k_{att,X}$; $k_{att,Ka} \approx 6 * k_{att,Ku}$)

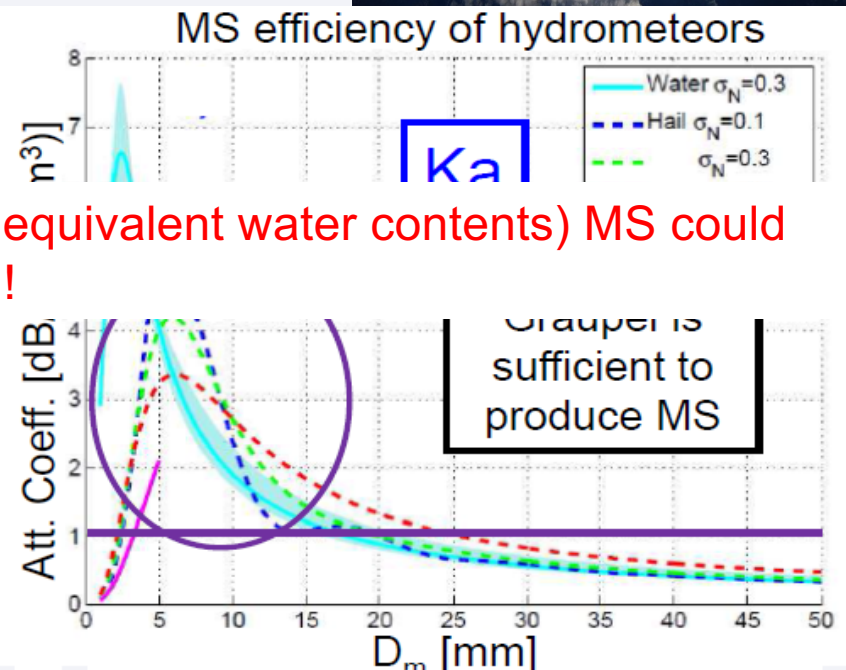
High scattering (ω close to 1) \rightarrow more MS for highly scattering particles (snow, graupel, hail)

Mean free path ($1/k_{att}$) smaller than FOV \rightarrow satellite-borne radars more prone to MS

- DPR beam width ≈ 5 km \rightarrow MS if $k_{att} > 1$ dB/km (roughly speaking)
- For a reasonable WC of 1 g/m^3 , classes producing attenuation higher than $1 \text{ dB/km}/(\text{g/m}^3)$ are prone to MS
- Water produces less MS because of its low ω



But with extreme storms (large hail, high equivalent water contents) MS could be detected in airborne as well and at Ku!



Multi-wavelength observations: the ultimate tool for MS detection

Multi-frequency observations are available from

- airborne (e.g. IPHEX X-Ku-Ka-W) (*smaller footprints but better sensitivity*)
- DPR (+collocated ground based NEXRAD)

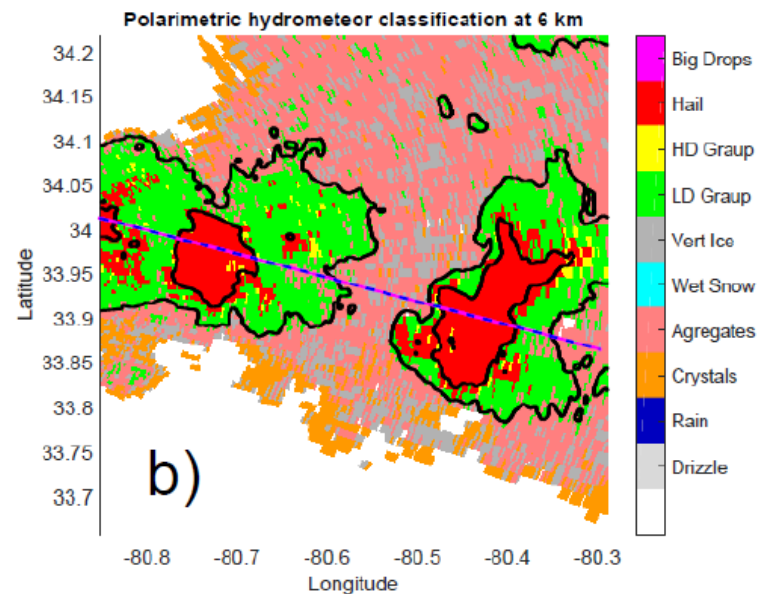
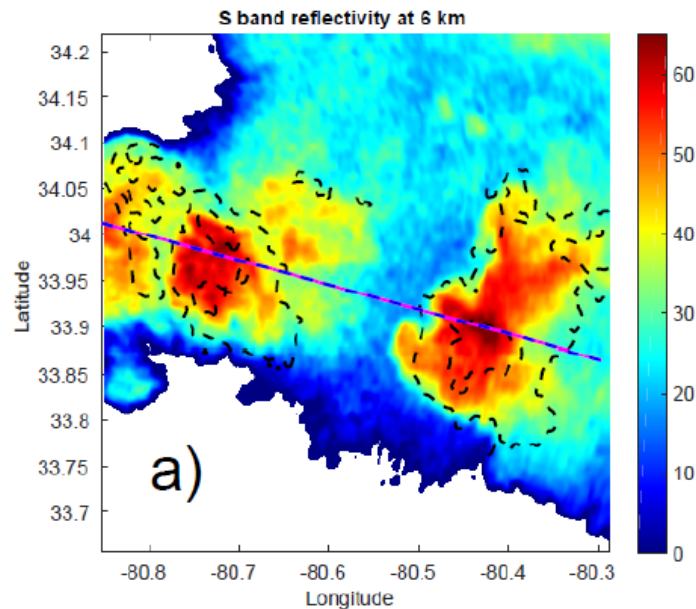
For deep convective scenarios the interpretation of dual-frequency observations requires to take into account multiple scattering.

Two examples:

- 1) Two hail bearing cells observed on May 23rd 2014 over North Carolina during IPHEX by the ER-2 instrument suite → unprecedented observations of deep convective cores via 4 radar and radiometer channels with freq. ranging from X- to W-band (3cm to 3 mm)
- 2) Tornadic supercell over Texas (Corpus Christi, 27May 2015) observed by the GPM-core observatory +collocated ground-basedWSR-88D S-band observations.

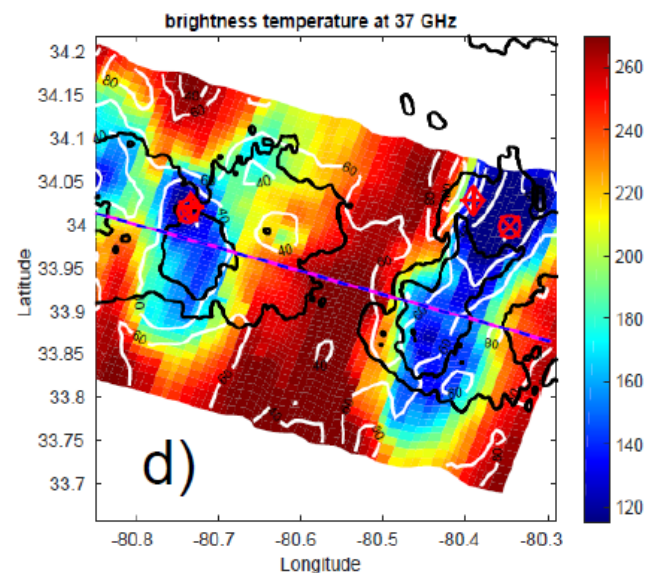
Goal: show the MS signatures and what we can and we cannot do (at the moment) in terms of retrievals

IPHEX May 23rd 2014 case: hail-bearing cells



**KCAE S-band
(3 GHz, 10 cm
wavelength)
Columbia, SC**

flight track **00:37-
00:41 UTC** (passing
through cell cores)



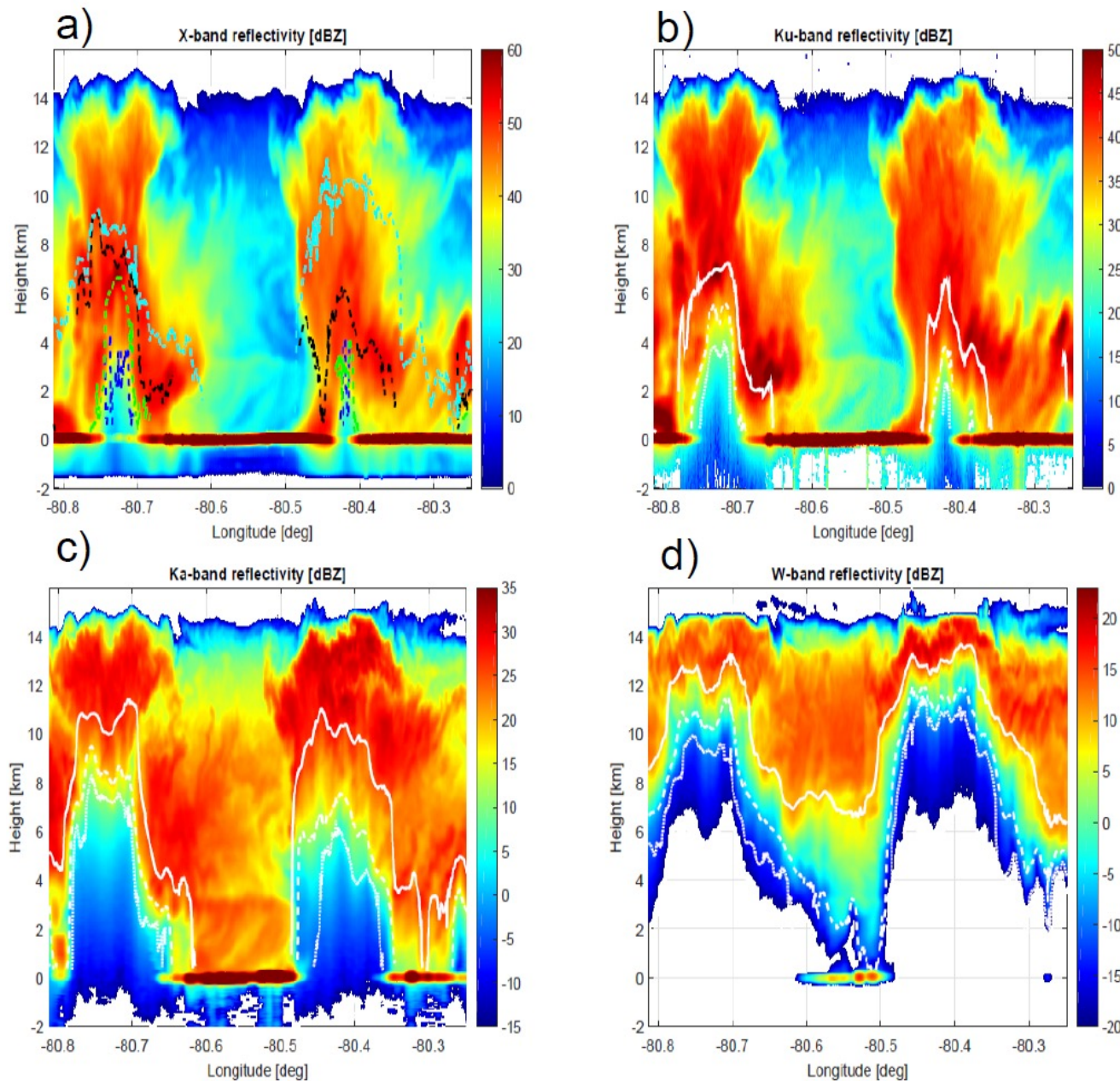
**AMPR
RADIOMETER**

**very cold
depression**

In the two cores:
214 K (223 K), 164
K (163 K),
115 K (95 K) and 91
K (56 K) for the 10,
19, 37 and 85.5

GHz → **hail
signature**

ER-2 obs: vertical structure from reflectivities



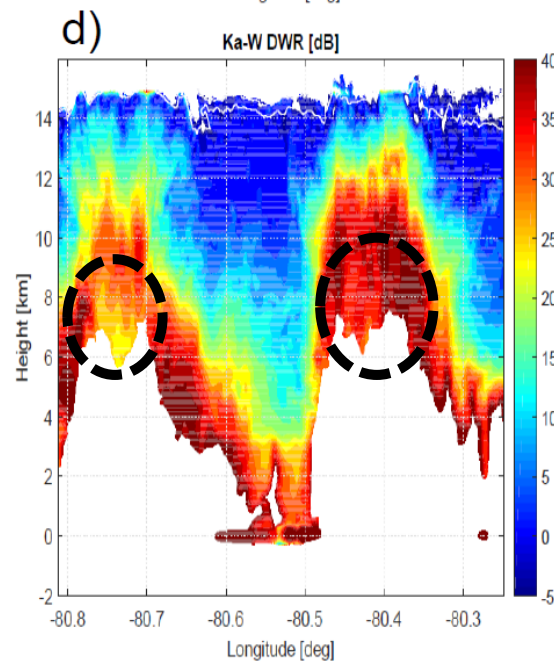
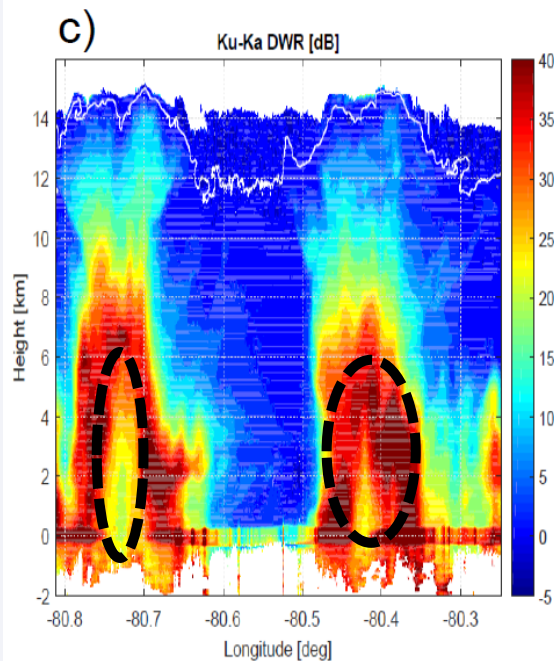
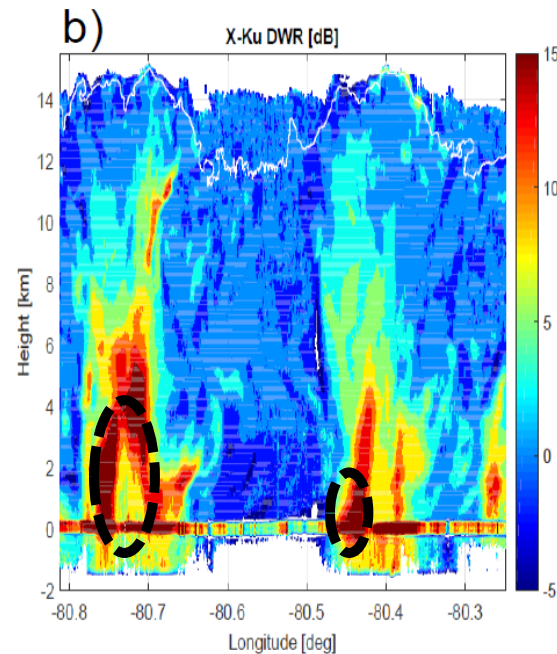
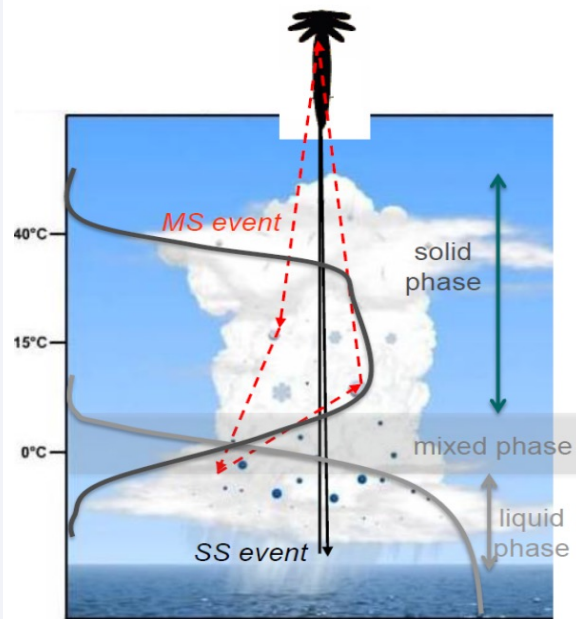
1) The deep convective system is reaching 14.5 km, v_D exceeding 30m/s

2) Attenuation signal clearly visible at X-band already below 4(3) km for the West (East) cell \rightarrow heavy rain pockets.

3) The higher-frequency radars are suffering from strong attenuation already in the upper levels, e.g. W-band at 12 km height \rightarrow radar signal below noise already at 7 km \rightarrow strongly absorbing ice \rightarrow high density

4) **Each frequency indeed effective down to the white dashed line**

ER-2 obs: Dual Wavelength Ratios



Three regions

- 1) In the upper part DWR is driven by Mie effects → retrieval of D_m
- 2) Below DWR is the result of combined non-Rayleigh and attenuation effects
- 3) In the center of the cells anomalous behaviour=DWR knee → signature of Multiple Scattering → MS so dominant in the highest frequency that it substantially compensates for the attenuation → the decrease of Z towards the ground is larger at the lowest frequency

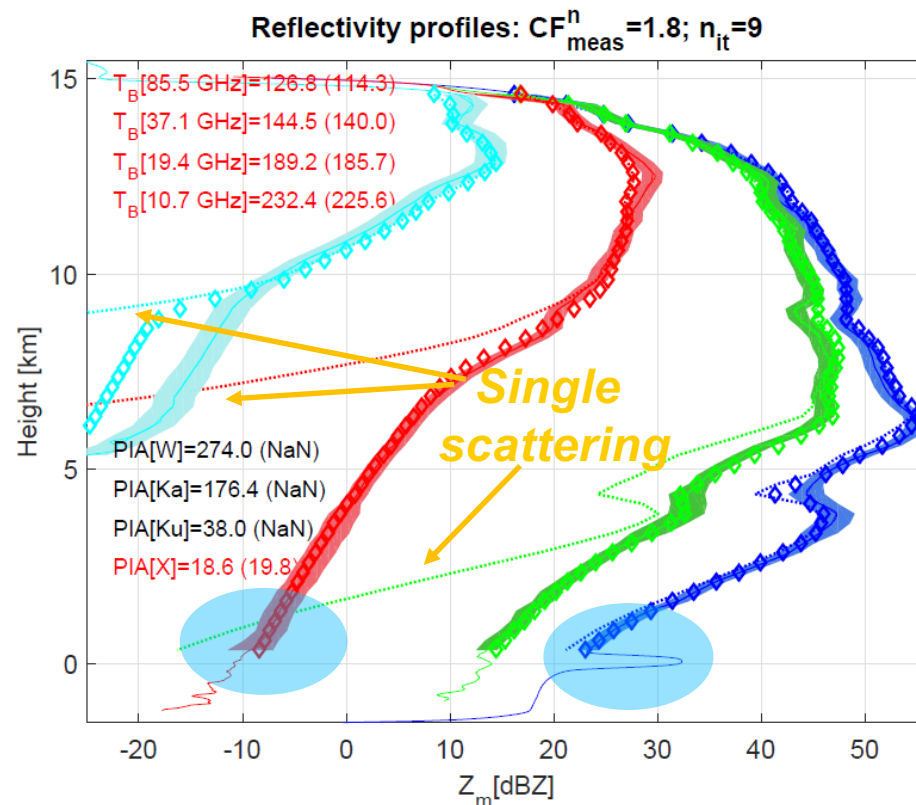
How can we disentangle Mie, attenuation and multiple scattering effects?

Retrieval: single profile

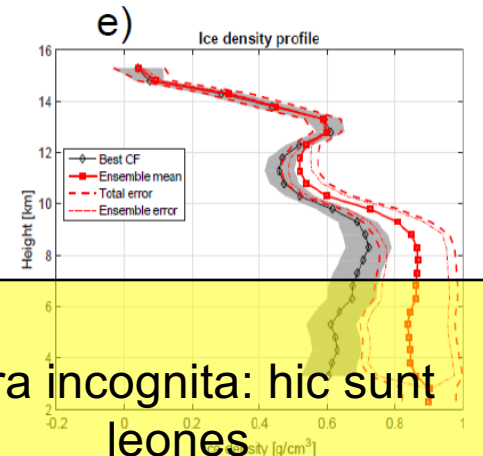
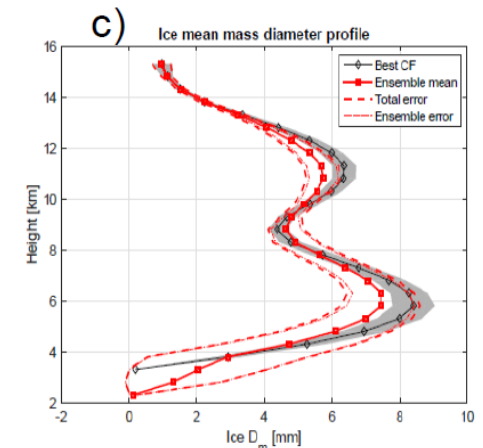
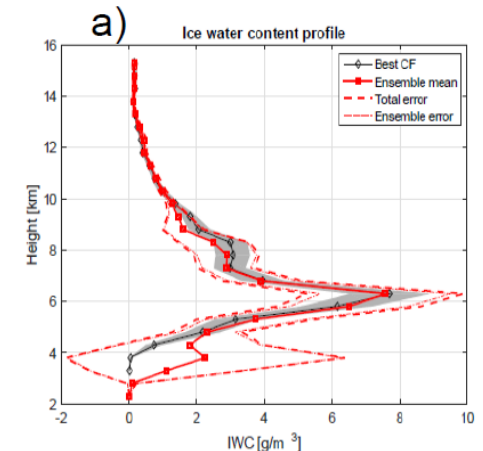
Based on OE:

- Forward operator based on *Hogan and Battaglia, 2008*
- With an ensemble of a-priori to scan through a variety of density and DSD assumptions
- Best solutions minimize

$$CF = \underbrace{[y - F(x)]^T S_\epsilon^{-1} [y - F(x)]}_{CF_{meas}} + \underbrace{[x - x_a]^T S_a^{-1} [x - x_a]}_{CF_{a-priori}}$$



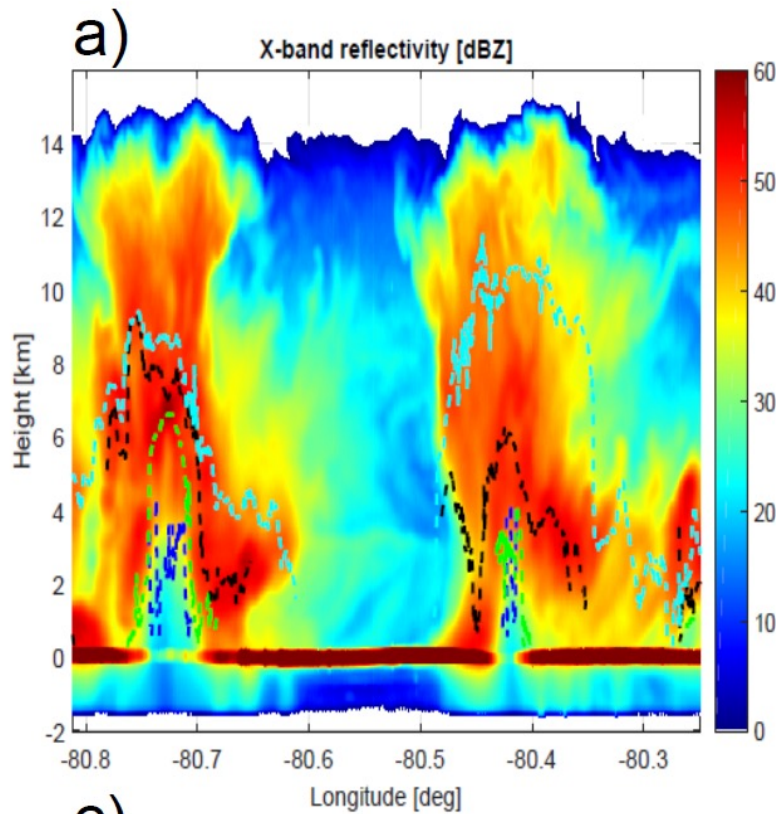
Unknowns
 IWC
 D_m
 ρ



Terra incognita: hic sunt
 leones

Details in Battaglia et al, JGR, 2016

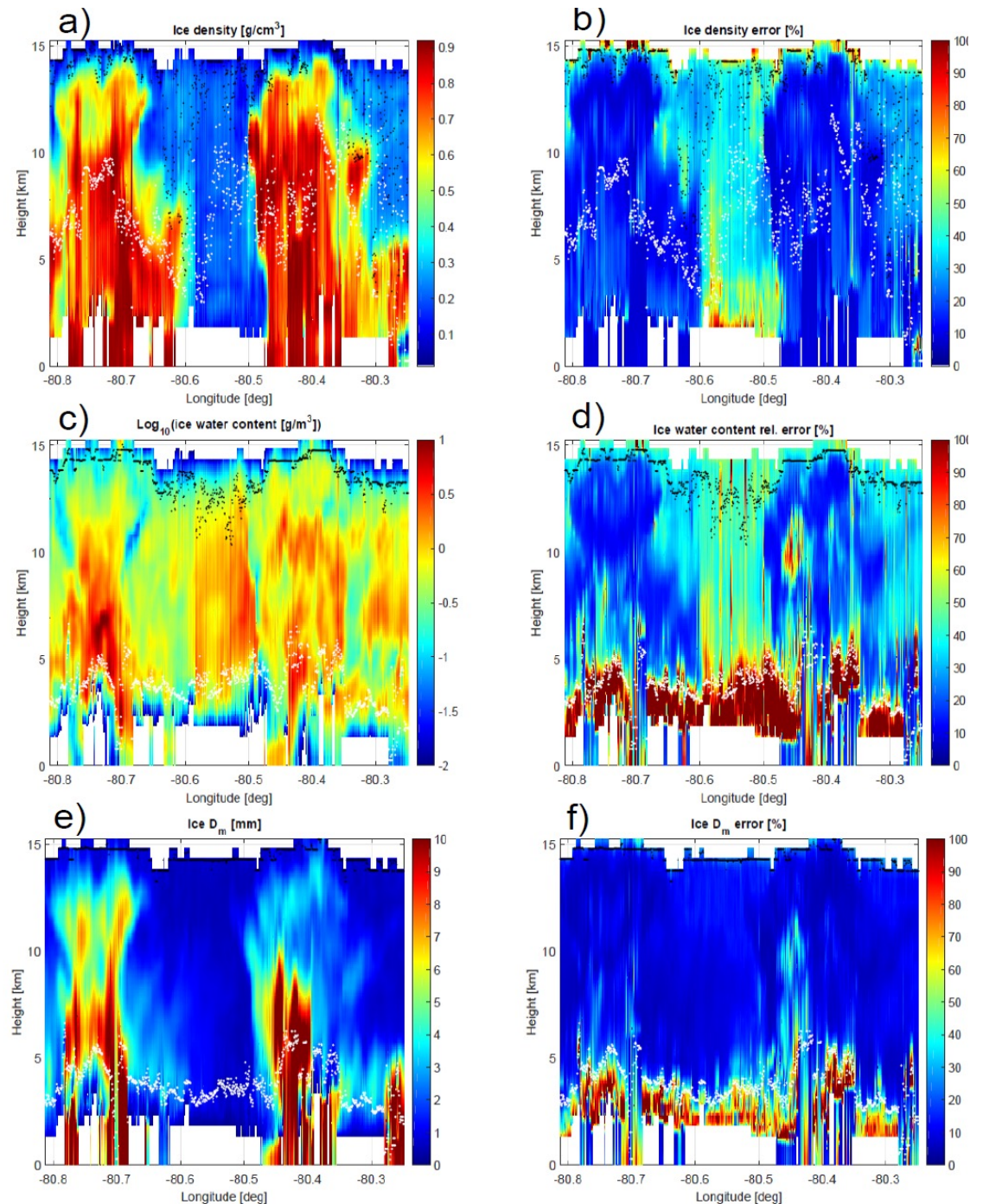
Retrieval: entire curtain



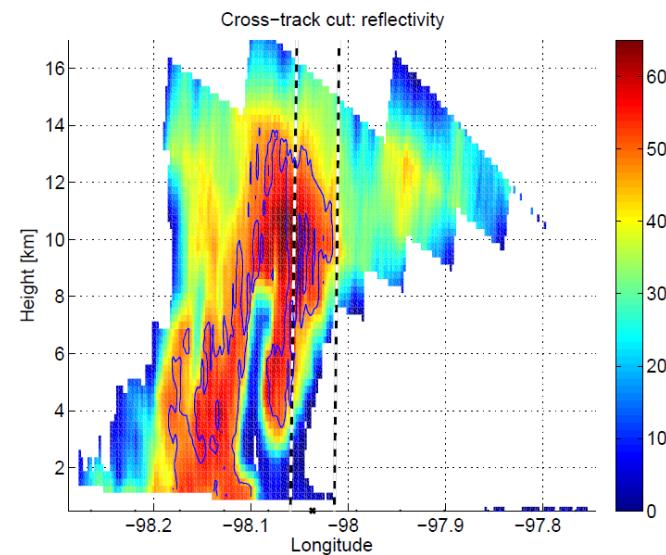
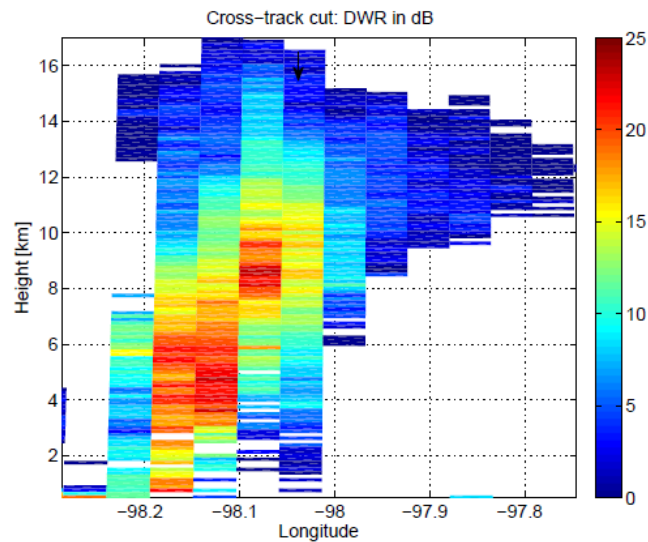
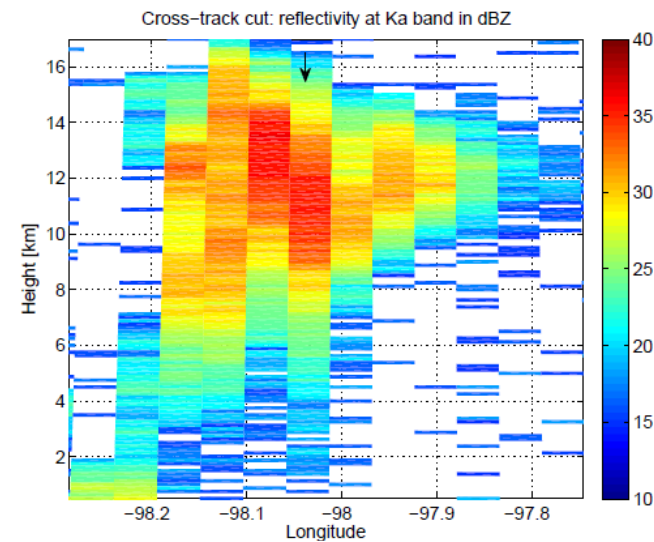
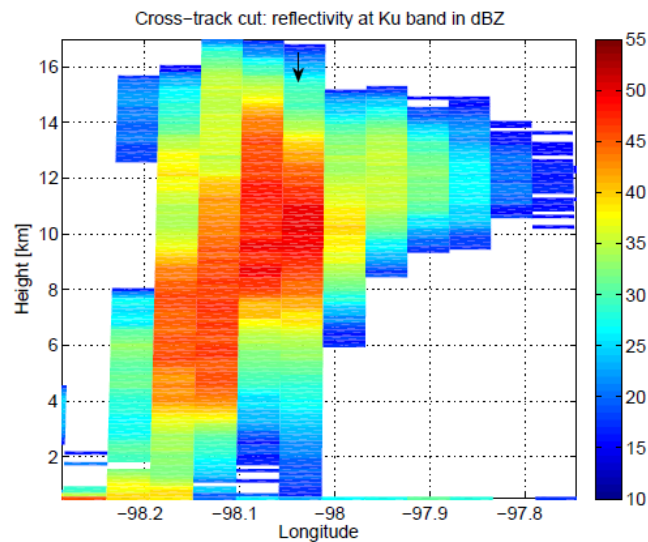
Core of convective cells are characterized by:

- Large ice densities ($>0.6 \text{ g/cm}^3$)
- Large IWC ($>5 \text{ g/m}^3$)
- Large particles ($D_m > 15 \text{ mm}$)

NB: retrieval becomes troublesome when entering the mixed-phase region



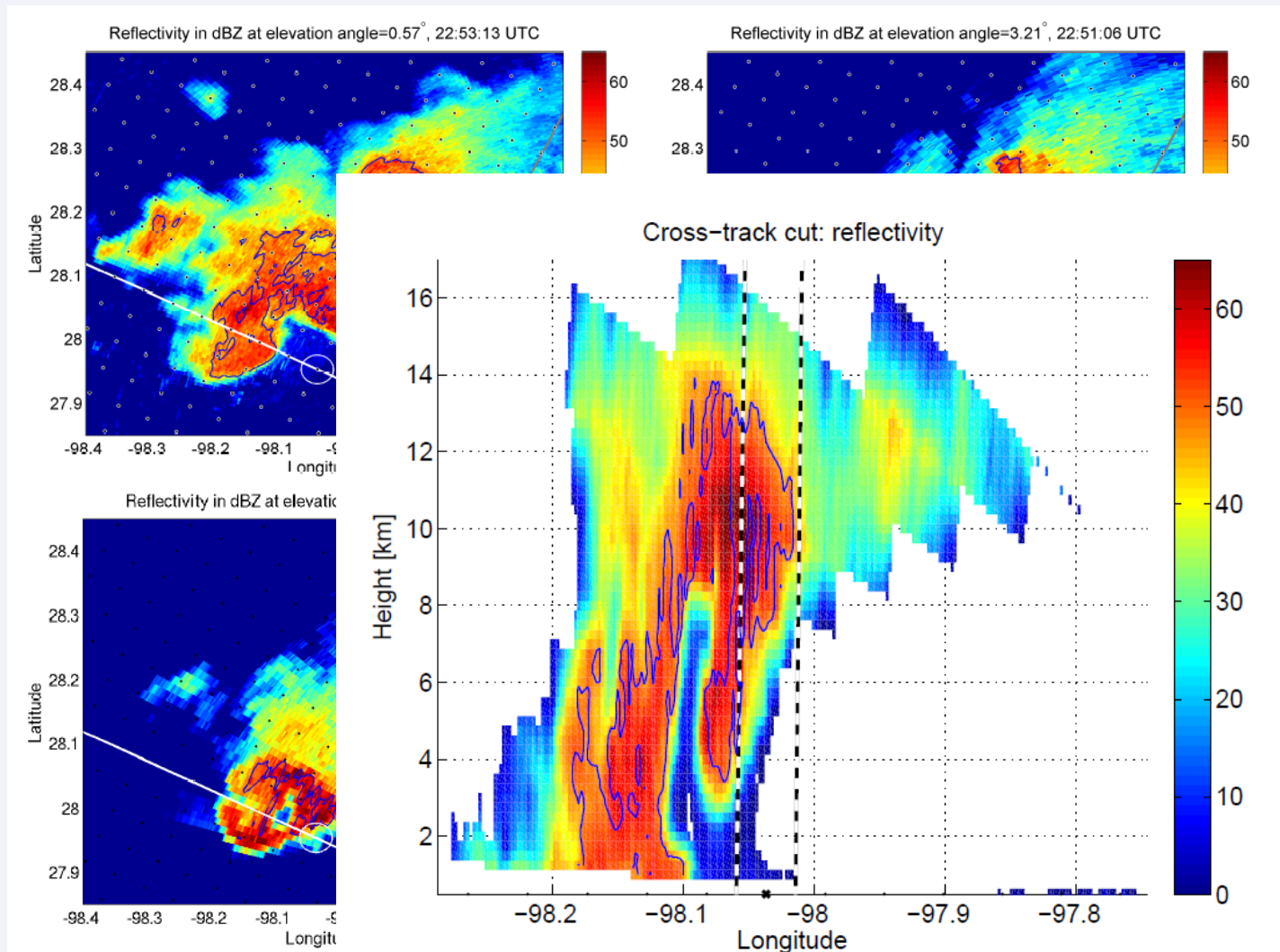
DWR knee with DPR: supercell over Texas



NEXRAD
S-band Z

MS with DPR: ground-based observations

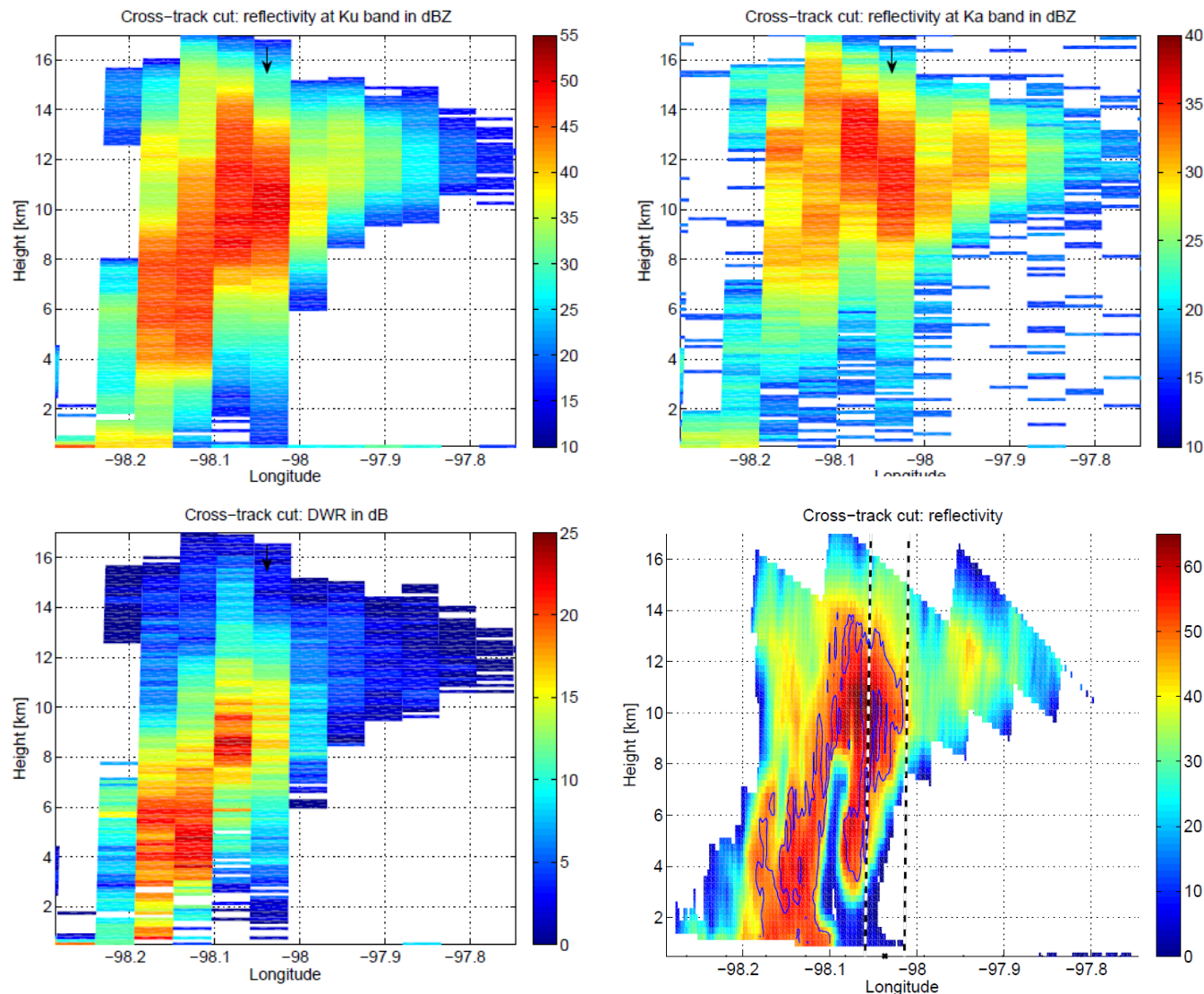
NEXRAD
S-band Z



- Tilted rotating updraft (white circle)
- Presence of hail (75% probability contour)

Heinselman and Ryzhkov, 2006:
Validation of polarimetric hail
detection. *Wea. Forecasting*,

MS with DPR: supercell over Texas



- Reconstruction of S-band “GPM-like” profiles (MRMS product, P. Kirstetter)

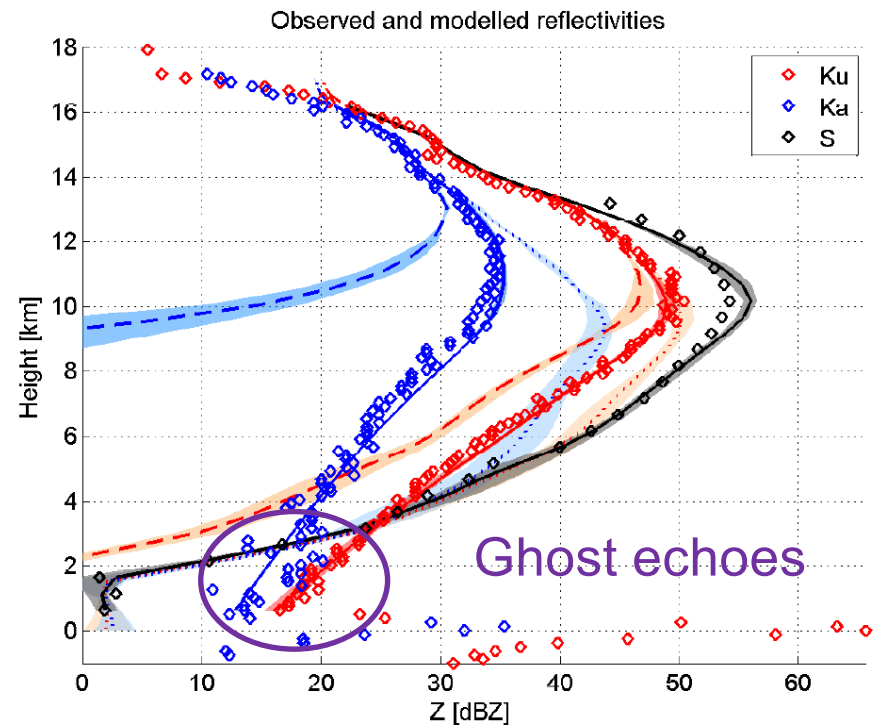
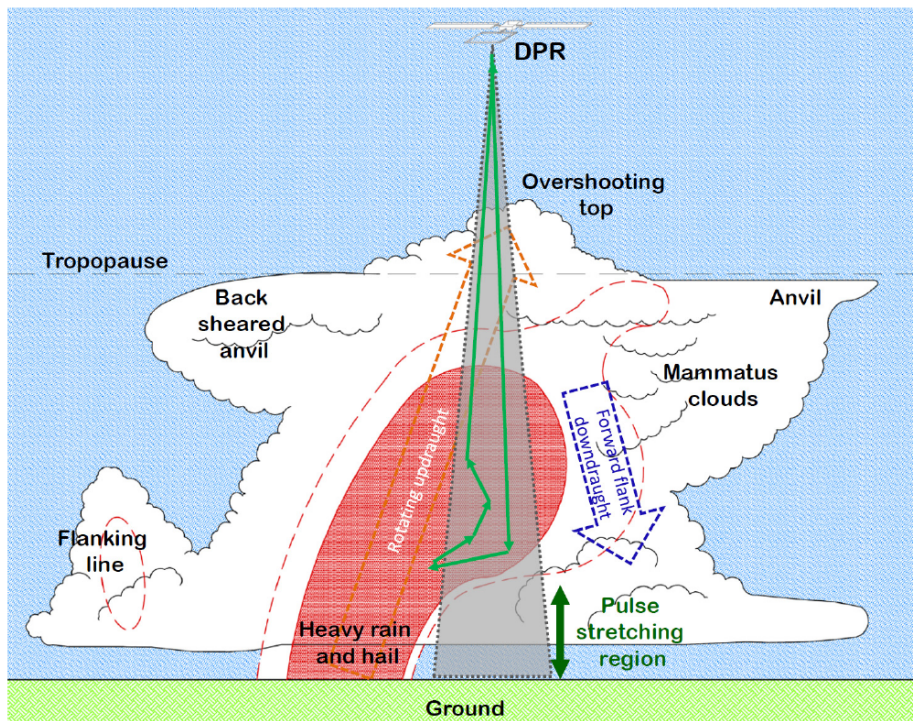
MS with DPR: Ghost echoes

- Triple frequency profiles

Validation of Ka-Ku retrieval by comparing forward modelled S-band reflectivity

Triple wavelength retrieval (support the presence of hail)

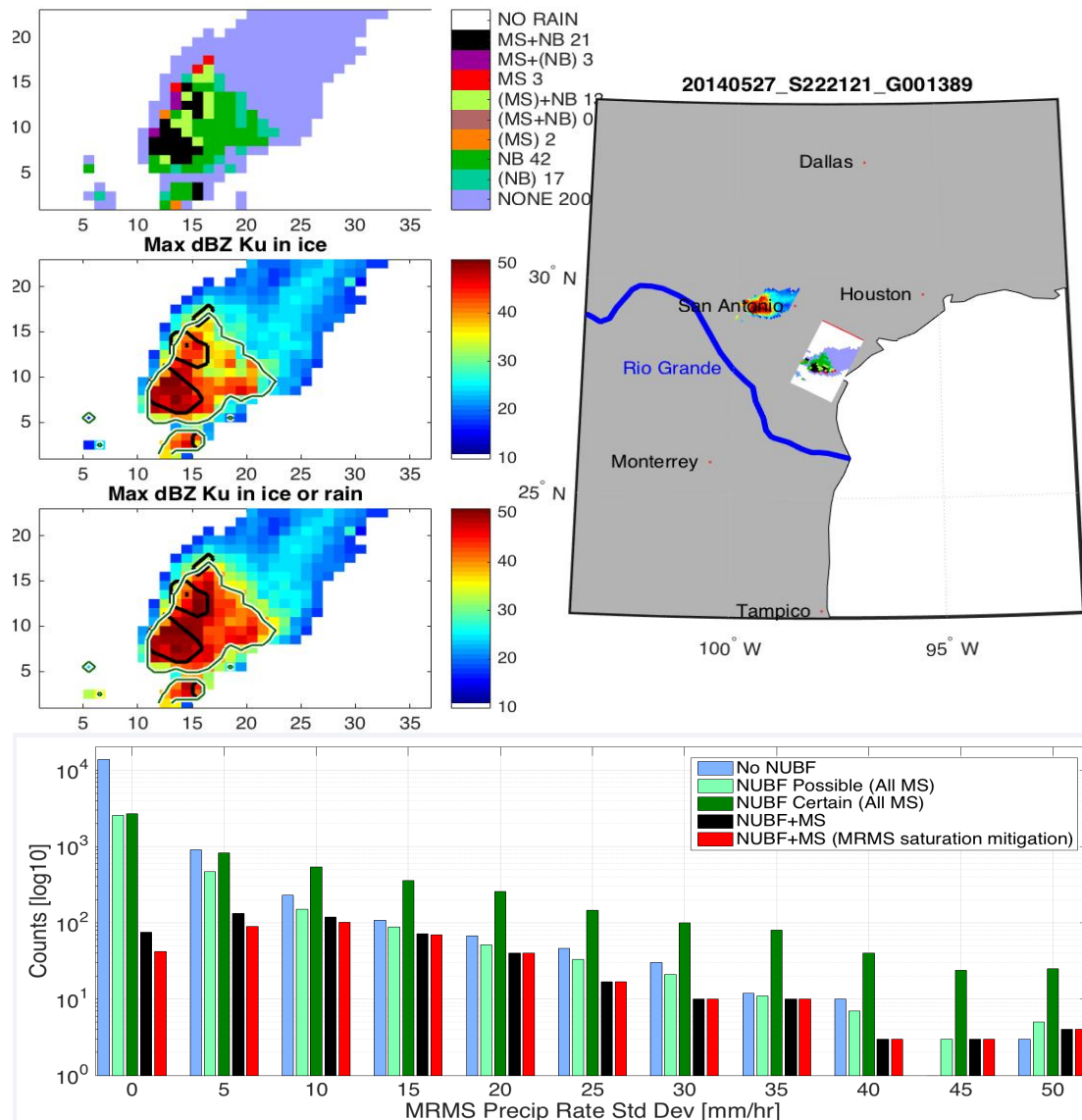
- Tilted convective core: no rain at the ground (S-band) → MS at Ka and Ku



Battaglia et al., 2016: Multiple-scattering-induced “ghost echoes” in GPM-DPR observations of a tornadic supercell, *J. Appl. Meteorol. Climatol.*

DPR algorithm: how to proceed (1)

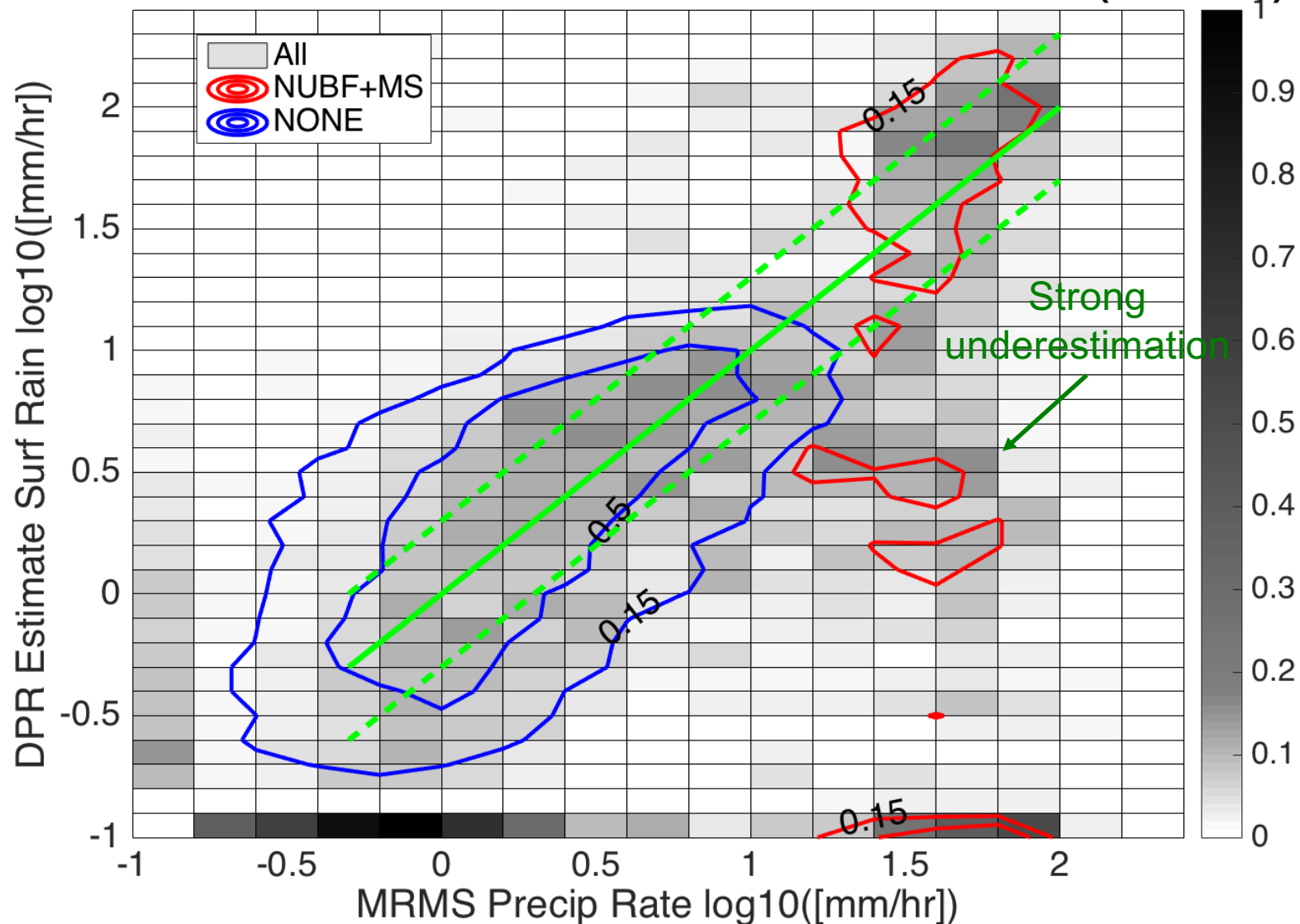
TRIGGER: Identification and flagging of DPR MS-affected and NUBF-affected profiles



1. Once flagged a specialized solver can be used for the retrieval.
2. For details on the Trigger (the 7th module mentioned by Iguchi-sama), and more results see Simone's talk on Thur @ DPR WG
3. An experimental version of the Trigger is fully integrated in a mock PPS. Transfer to PPS to happen as soon as it is authorized by license control.
4. Validation is in progress with MRMS
5. The OE solver could kick in only in the "red purple and black" profiles.

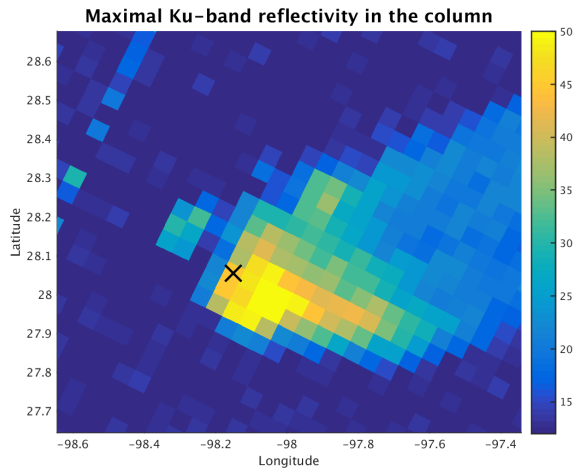
Proportion of NUBF increasing with increasing std of MRMS

TRIGGER Portion of DPR V03B vs MRMS'16 Gran. 1K-3K (37 cases)

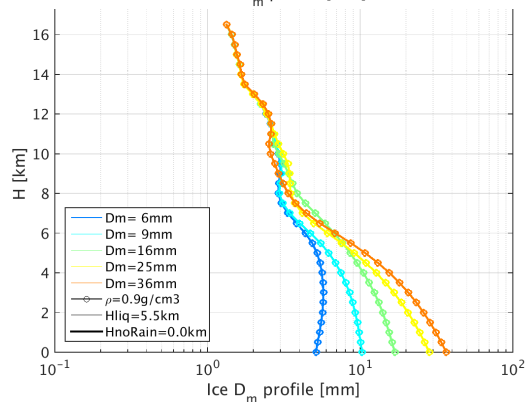
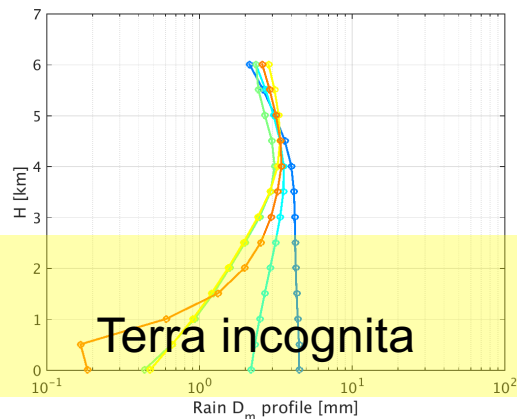
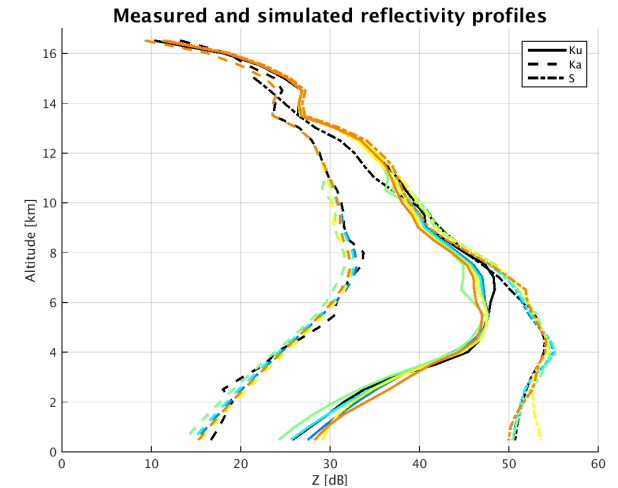


In most occurrences DPR is doing OK, especially in low to moderate rainfall.
But the rare intense cases are often bruising the stats.

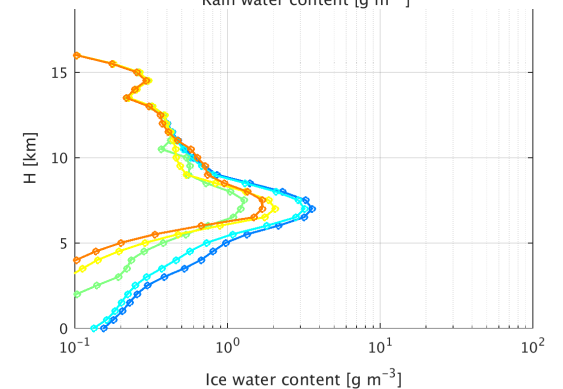
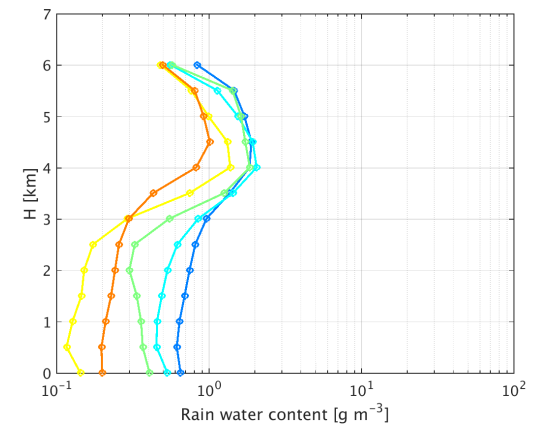
Solver algorithm for MS



Using an ensemble of a-priori assumptions about micro-physical properties of hydrometers we are able to fit triple frequency measurements well, but...



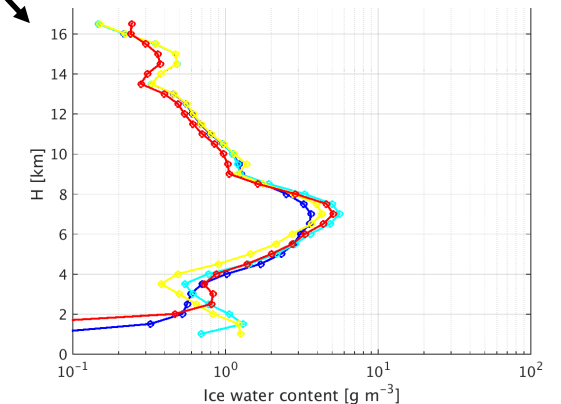
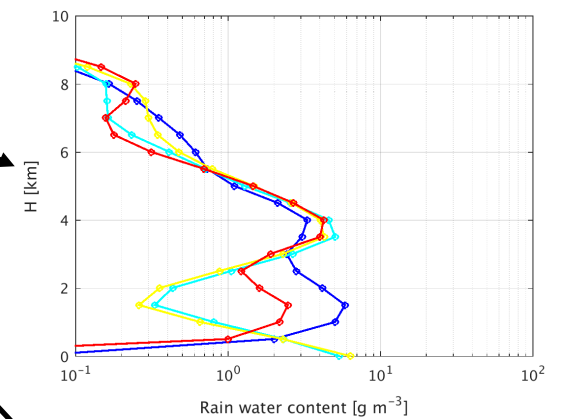
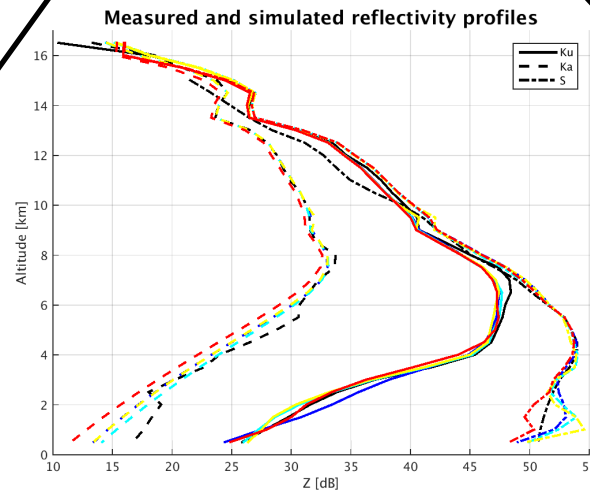
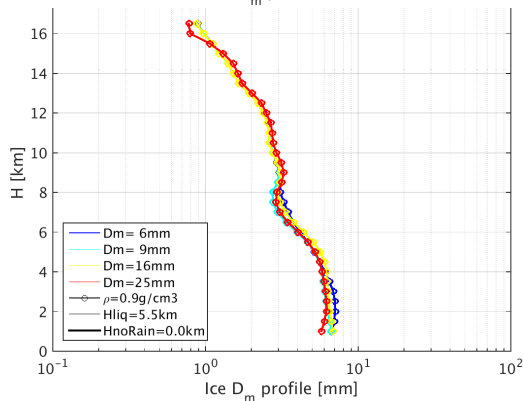
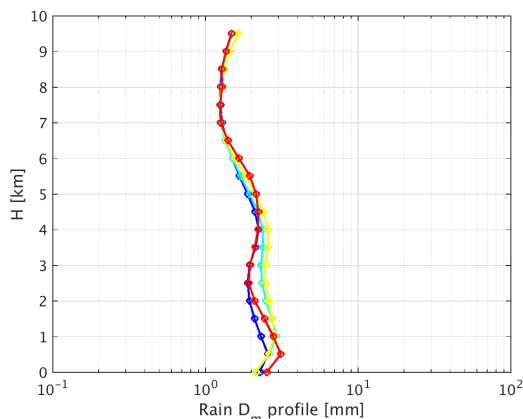
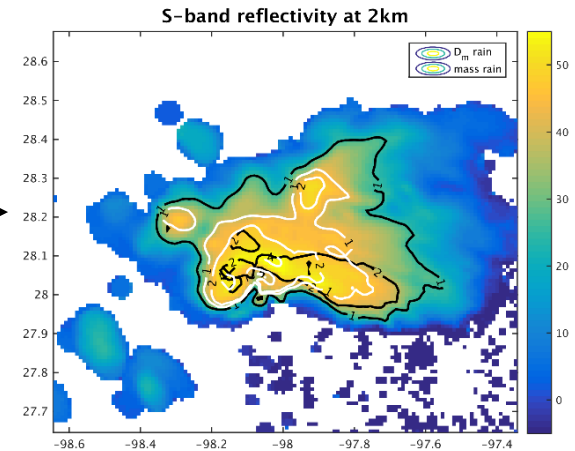
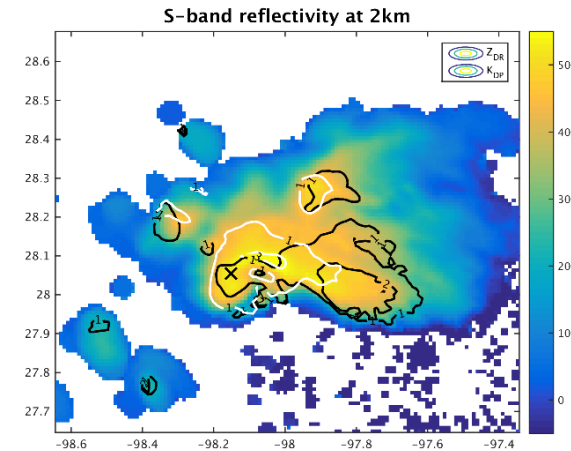
MULTIPLE SOLUTIONS
minimize the cost function.



Solver algorithm for MS

S-band polarimetric
measurements
used to estimate D_m and WC
(Straka et al. 2000,
Cifelli et al. 2002,
Carey and Rutledge 2000)

The solution space
greatly reduced



Conclusions

There are some unequivocal signatures of multiple scattering, especially when multi-wavelength radar observations are available (e.g. DWR knee).

Multi-frequency airborne and collocated DPR and ground-based observations have demonstrated that **MS are present certainly at Ku band and likely at X-band when hail is present in the column**. One-way PIA can reach 20~dB at X-band and values larger than 40~dB at Ku-band → **estimates of precipitation as derived from Ku-band space-borne radars** must be taken with extreme caution in presence of dense, ice-laden convective cells.

A **trigger algorithm**, capable of identifying and flagging profiles affected by MS based on the morphology of Ku and Ka Z-profile, is up and running in a mock PPS.

Work in progress on the solver → “terra incognita” approach: identification of proper a-priori for reducing the space of solutions based on more than two years of deep convective storms over CONUS where NEXRAD collocated data are available.

Thanks for your attention



How frequent are they?

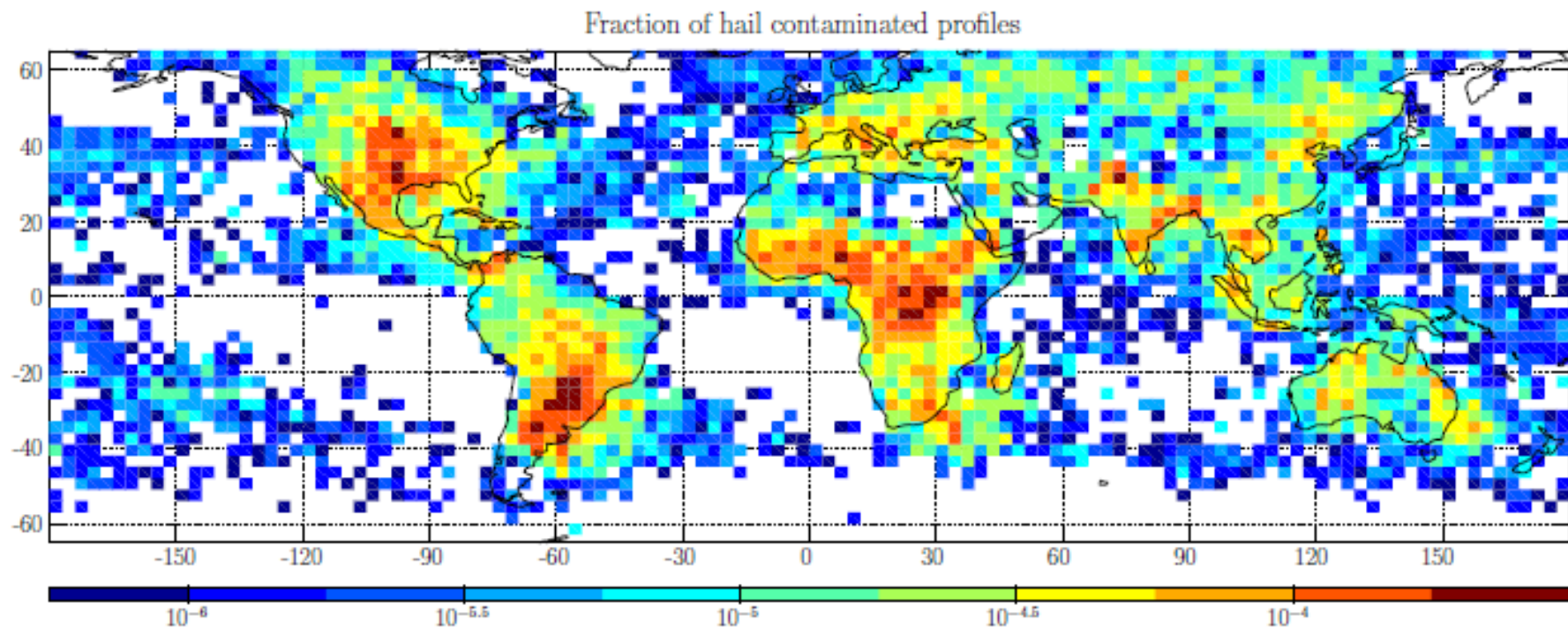


FIG. 13. Global map of the fraction of the DPR profiles that contain hail, based on the Z_{mix}^{Ku} proxy.